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Space Reactor/Stirling Cycle Systems for High Power Lunar Application

Paul C. Schmitz
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Lee S. Mason
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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SPACE REACTOR/STIRLING CYCLE SYSTEMS FOR HIGH POWER LUNAR APPLICATIONS

Paul C. Schmitz
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

Lee S. Mason
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

INTRODUCTION

NASA's Space Exploration Initiative (SEI) has proposed the use of high power nuclear power systems on the lunar surface as a necessary alternative to solar power. Because of the long lunar night (~14 earth days) solar powered systems with the requisite energy storage in the form of regenerative fuel cells or batteries becomes prohibitively heavy at high power levels (~100 kWe). At these high power levels nuclear power systems become an enabling technology for variety of missions. One way of producing power on the lunar surface is with an SP-100 class reactor coupled with Stirling power converters. In this study, analysis and characterization of the SP-100 class reactor coupled with Free Piston Stirling Power Conversion (FPSPC) system will be performed. Comparison of results with previous studies of other systems, particularly Brayton and Thermionic¹, are made.

ANALYSIS

Analysis and characterization of a nuclear reactor power system to meet the requirements of Case 5A (Case 5 with insitu resource utilization) of NASA's 90 day study is performed.² Table 1 shows the requirements for this lunar base. Fig. 1 shows the plant configuration considered in this study. It makes use of the lunar soil to provide the majority of the radiation shield by placing the reactor in an excavation. This also allows maintenance to be performed on all systems outside the reactor cavity. To provide commonality with the other systems previously studied the system was designed to produce 1000 Volts DC output 250 meters from the source. Redundancy for the system is provided by having six converters operational at any one time with two additional converters as backup.

TABLE 1.
Lunar Base Power System Requirements

Power Output to Switch Gear	550 kWe
Life of Power System	10 Years
Equivalent Sink Temperature Assumed	250 K (Vertical Radiator with Reflective Blanket)

Characterization of the components which make up the system is performed by making mass and efficiency estimates for each of them as a function of the electrical or thermal power required. With electrical power fixed a temperature ratio and Stirling converter specific mass is chosen. From this the efficiency of the Stirling converter is found and the amount of heat input and heat rejection can be calculated. The various components are then sized to meet these requirements. The minimum mass point for a given power level is found by varying these system parameters. The maximum temperature

of the system is set by material considerations either in the power conversion device or in the reactor. The various components used to make up the system are described below.

Reactor

The reactor is modeled by RSMASS.³ RSMASS is a modeling tool used to predict the mass of a reactor and shield. Although the majority of shielding is provided by the lunar soil, shielding is required for the instrumentation and control systems in the excavation. The instruments needing the most shielding are the multiplexers and these set the dose requirements. Dose fluences allowed at the multiplexers (located 1.5 meters from the core) are 1.6×10^{15} nvt and 1.2×10^8 rad, which is consistent with the SP-100 design. The maximum bulk fluid temperature out of the reactor is 1375 K.

Stirling Power Conversion Units (PCU's)

The Stirling PCU's are modeled using Mechanical Technology Inc. (MTI) scaling study results.⁴ The scaling study provides efficiency as a function of temperature ratio, power output per engine, and the specific mass of the converter. The model is based on MTI's dual opposed Stirling Converter. The two heater head temperatures which are considered in this analysis are 1050 K and 1300 K. This study assumes the 1050 K and the 1300 K power converters have similar mass and efficiency trade-offs.

Intermediate Liquid Metal Loop

It is desired to prevent activated coolant from leaving the reactor excavation and to provide power conversion redundancy. One method of achieving this is by placing an intermediate heat exchanger, pumps, piping, accumulators, coolant, decay heat pump, and insulation between the reactor and the Stirling converters. This effectively decouples the primary loop from the Stirling converters and prevents the activated coolant leaving the hole while providing independent loops to the Stirling converters. The lithium to NaK heat exchangers plus the requisite pumps, piping, etc. are modeled as a function of thermal power.

Radiator

Two different types of heat rejection subsystems are used for the two systems studied. The 1050 K system uses a NaK pumped loop coupled to a water heat pipe radiator while the 1300 K system uses a liquid metal pumped loop radiator. Because of the high rejection temperature of the 1300 K system, water heat pipes were not possible. Mercury heat pipes are a candidate but were not chosen because of vehicle contamination concerns. Because the Stirling converter operates at nearly constant rejection temperature the temperature drop from the inlet to the outlet of the radiator is small. Both these radiator concepts are under development at NASA Lewis Research Center under the Civil Space Technology Initiative (CSTI) High Capacity Power Project and have radiator specific mass goals of 5.0 kg/m^2 . The study assumes that these radiator goals can be met. A highly reflective blanket is placed underneath the radiators to reduce the effective lunar sink temperature from 325 K to 250 K. The design and redundancy of the Stirling Power converters and radiators is identical to that of Mason and Bloomfield providing an effective sink of 250 K in the spoked wheel configuration.⁵

Linear Alternator Radiator

Because of the temperature constraints on the linear alternator imposed by the samarium-cobalt magnets, a cooling loop for the alternator is required when the temperature of the alternator exceeds 525 K. Because of the small size of the radiators, pumps and ducting are a larger percent of the system mass and require a heavier, 7.5 kg/m^2 specific mass radiator. This is provided by a NaK pumped loop system coupled with water heat pipes. The thermal power required to be rejected is

based on the temperature ratio of the Stirling converter and the temperature difference between the cooler heat exchanger and the linear alternator.

Power Conditioning

FPSPC's have the potential of producing a variety of output voltages. Increases in output voltage are accomplished by increasing the wire turns in the alternator. As the voltage increases, the size of the wire can decrease because of the associated decrease in current. Insulation thickness stays relatively constant because the voltage between turns is maintained at approximately 5 volts. Therefore, as alternator voltage increases, a negligible increase in converter mass results. An output voltage of 1000 Vrms was chosen.

The mass of the capacitors to correct the power factor to unity is included in the mass of the Stirling converters.

To meet the requirement of 1000 volt DC output, power conditioning in the form of a rectifier and filter is needed. Rockwell developed models to estimate the mass of these components, and they are used in this study.⁶ Radiators are required to reject the heat produced by inefficiencies in the PMAD systems, and these are also modeled. Fifteen meter aluminum cables are used to couple the Stirling PCU's to the rectifier. A single 250 meter cable will take the conditioned 1000 Volt DC power to the switch gear which links this to the lunar electrical power grid.

RESULTS

Fig. 2. shows the surface representing total system mass that is generated by varying both temperature ratio and Stirling converter specific mass for a 1050 K, 550 kWe Stirling lunar base application. The tradeoff between high efficiency heavy Stirling converters and light weight, less efficient converters is seen. It should be noted that some points on the surface are extrapolated beyond the range of the scaling study results. None of the systems considered optimized at these extrapolated points. Table 2 shows the mass breakdown at 550 kWe for 1050 K and 1300 K heater head temperatures. The 1050 K Stirling converter optimizes at a temperature ratio of 2.0 and a Stirling converter specific mass of 4.8 kg/kWe. At a temperature ratio of 2.0, (cooler heat exchanger temperature of 525 K) the linear alternator radiator is not required. The 1300 K system has a minimum mass at temperature ratio of 2.3 and a converter specific mass of 4.0 kg/kWe. Compared to its lower temperature counterpart it offers a reduction in mass of 20% and a reduction in radiator area of 45 %. At converter cold-end temperatures above 525 K the alternators must be cooled. The minimum mass 1300 K system requires a linear alternator radiator of 34.21 m² which weighs 342.08kg.

Besides the 550 kWe design point, it was also desired to look at how a lunar base power plant would scale with various electrical power levels. System studies were made at 100 and 1000 kWe levels. This represents the current range of power levels envisioned for this class of Stirling converters. Fig. 3 shows system mass and radiator area as a function of power level. At each power level both Stirling converter specific mass and temperature ratio are varied to arrive at a minimum overall system mass. As the electrical power level increases, the mass of the radiator becomes a more significant part of the system mass. This makes the advantages of high temperature (i.e.1300 K) more important.

Several other types of nuclear reactor power systems could be utilized to produce the required electrical power. Two of the more promising systems, Brayton and incore Thermionics have been modeled at 550 kWe to the same requirements.

Two Brayton systems are considered, the first operates at a turbine inlet temperatures (TIT) of 1140 K (corresponding to the mini BRU program⁷) while the second utilizes high temperature refractory metal components and operates at a TIT of 1300 K. The Brayton system analysis was done for a recuperated Brayton cycle with a SP-100 reactor and includes a liquid metal to gas heat exchanger to transfer heat to the working fluid. This heat exchanger is in the reactor cavity (as is the case for the Stirling and thermionic systems) and does not permit activated coolant to leave the excavation and also provides redundancy for the power converters. The mass algorithms for the Brayton cycle are based on CCEP⁸ while the reactor and shield are sized using RSMASS. Temperature ratio, pressure ratio,

and recuperator effectiveness are varied to find the minimum system mass. The same redundancy is used in the Brayton system as in the Stirling systems.

The baseline thermionic system assumed ± 7.5 Volt reactor output, a conservative interelectrode gap and a 1800 K emitter temperature. The advanced thermionics assumed a ± 50 Volt output, a reduction in interelectrode gap and a 20000 K emitter temperature. The largest single impact on the thermionic system mass was the assumption of higher output voltages from the reactor core. These advanced goals with higher output voltage is not part of the TFE program and several issues must still be resolved before this higher output voltage is possible. The requirement that no activated coolant leaves the excavation is applied to all the systems considered.

Fig. 4 shows a comparison of the Stirling system to the other systems based on mass. Of the near term technology systems (i.e the 1050 K Stirling, 1140 K Brayton, and Baseline thermionics) the Stirling system provides minimum mass. All three of the advanced technology systems provide, within the accuracy of this study, the same mass. Fig. 5 shows a radiator area comparison with the baseline and advanced thermionic systems providing the smallest radiator areas. The reason the thermionic systems have small radiators is that their rejection temperature is around 900 K. Although the advanced thermionic system has the smallest radiator, the 1300 K Stirling system is a close second. The high temperature Brayton and the low temperature Stirling have similar radiator areas.

A 10% reduction in mass can occur for the Stirling systems if the intermediate liquid metal loop is removed. Alternate low mass approaches for the intermediate loop are currently being studied; these would maintain the goal of isolating the reactor loop and allowing converter maintenance. Two other approaches allow the removal of this loop. The first is to allow activated coolant to pass over the heater heads of the Stirling converters and only permit maintenance after the coolant activation has decreased. The second is to place the Stirling converters in the reactor excavation. This method precludes maintenance. These options need to be examined further.

CONCLUSION

Stirling converters at both the 1050 K and 1300 K heater head temperatures offer low mass, high efficiency systems for lunar base applications. Both high and low temperature Stirling systems have the benefits of fitting into the SP-100 reactor program while providing reductions in radiator mass and size when compared to Brayton power conversion systems. Low temperature Stirling systems offer the lowest mass of all the low temperature systems considered. Of the high temperature Brayton, Stirling, and thermionic systems considered, all are comparable in mass. A significant reduction in radiator area over the Brayton systems can be achieved if the thermionic or high temperature Stirling systems are used. One draw back of these thermionic reactor systems are that if the advanced technology goals are not met, this reactor/power conversion system can not be coupled with other power conversion schemes.

At 100 kWe a reduction in specific mass from 35.2 kg/kWe to 31.2 kg/kWe (a 10% reduction in system mass) occurs when going from 1050 K to 1300 K heater head temperatures. At 1000 kWe the reduction in specific mass is from 19.1 kg/kWe to 15.2 kg/kWe, or a 20% reduction in system mass. At 550 kWe the reduction in specific mass is from 20.5 kg/kWe to 16.8 kg/kWe, or a 18% reduction in system mass. For the 550 kWe system the total radiator area is reduced from 628.46 m² to 356.45 m². This decrease in radiator area is the primary reason for the reduction in system mass. This clearly shows the increasing importance of high temperature converters as the electrical power output increases

1 L. Mason ,P. C. Schmitz, and D. Gallup 'Lunar In-Core Thermionic Nuclear Reactor Power System Conceptual Design', Eighth Space Nuclear Power Symposium, January, 1991.

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 - 5 L. Mason, H. Bloomfield, and D. Hainley, "SP-100 Power System Conceptual Design for Lunar Base Applications", Sixth Space Nuclear Power Symposium, January 1989
 - 6 K. Metcalf, "Lunar/Mars Mission Energy/Power System Assessment Studies", NAS3-25808, Rockwell International, August, 1990.
 - 7 R. E. English, "Power Generation from Nuclear Reactors in Aerospace Applications", NASA Technical Memorandum TM 83342, November 1982.
 - 8 J. Klann, "Analysis and Selection of Design Conditions for a Radioisotope Brayton-Cycle Space Powerplant", NASA Technical Note TN D-4600, June 1968.

TABLE 2.
550 kWe Stirling Power Converters

	Low Temp	High Temp
Heater Head Temp	1050 K	1300 K
Temp Ratio	2	2.3
Cycle Efficiency	28.98%	33.50%
Radiator Area	628.32 m ²	356.45 m ²
Linear Alternator Radiator	0.0 m ²	34.2 m ²

Mass Breakdown of System (kg)

Reactor	1047.6	1042.8
Shield	386.5	374.22
Intermediate Liquid Metal Loop	797.8	712.32
Liquid Metal Pumps	692.34	645.03
Primary Piping, Accum, etc.	748.35	667.9
Stirling PCU/Alternator	3610.26	3008.5
Main Radiator	3142.29	1782.2
Alternator Radiator	0	342.08
Structure	1146.78	943.27
Reactor Bulkhead	783	783
Upper Scatter Shield	112.1	112.1
Reactor Support Stand	52.3	52.3
Excavation Sleeve	56.5	56.5
Excavation Cooling System	49.5	49.5
Transmission Line (250 m)	479.1	479.1
Power Conditioning		
Rectifier	188.08	188.08
Filter	150.87	150.87
Enclosure	217.61	217.61
Radiator	171.22	171.22
Misc.	101.29	101.29
Total Base Mass (kg)	13933.5	11879.9

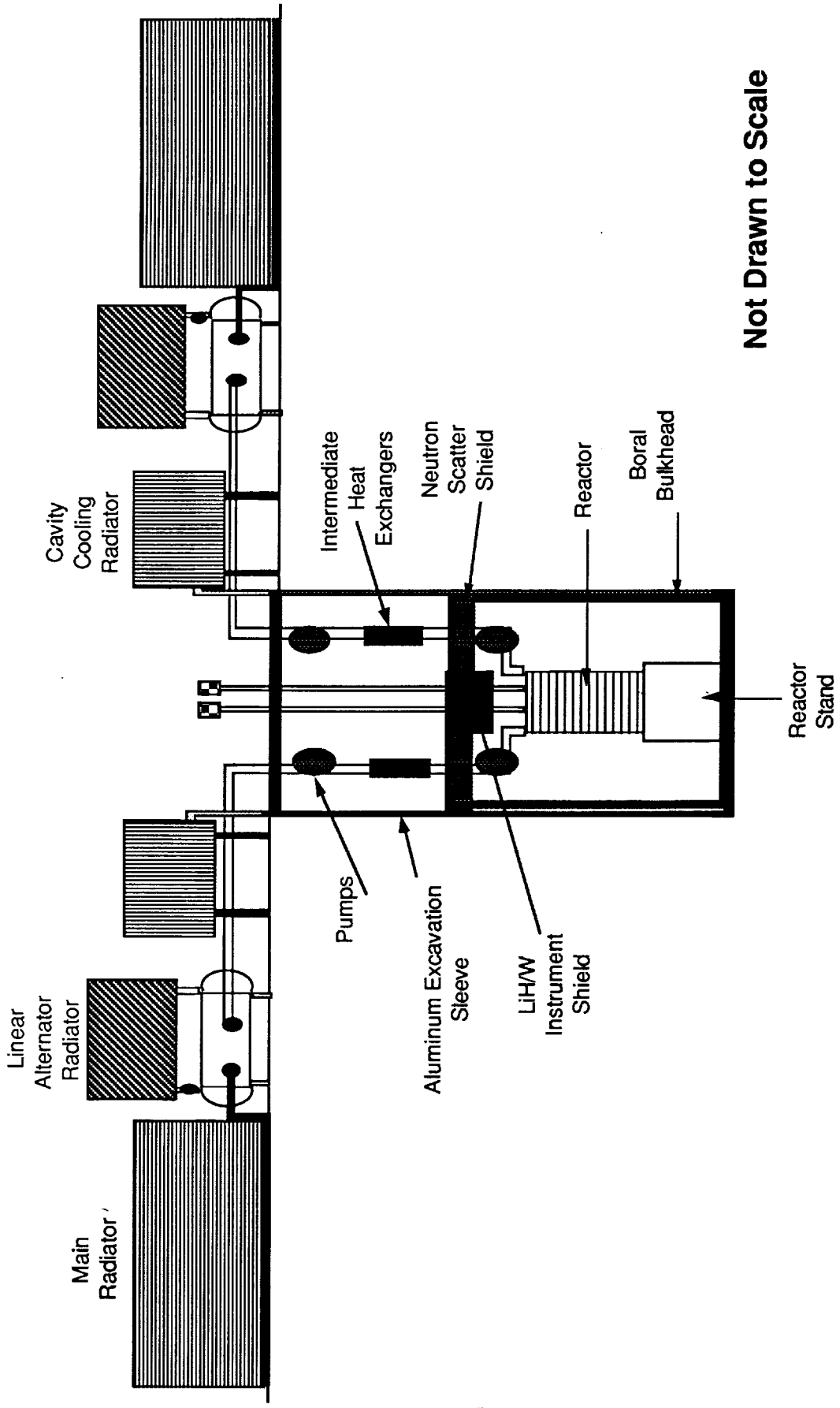


FIGURE 1. Lunar Base Cutaway

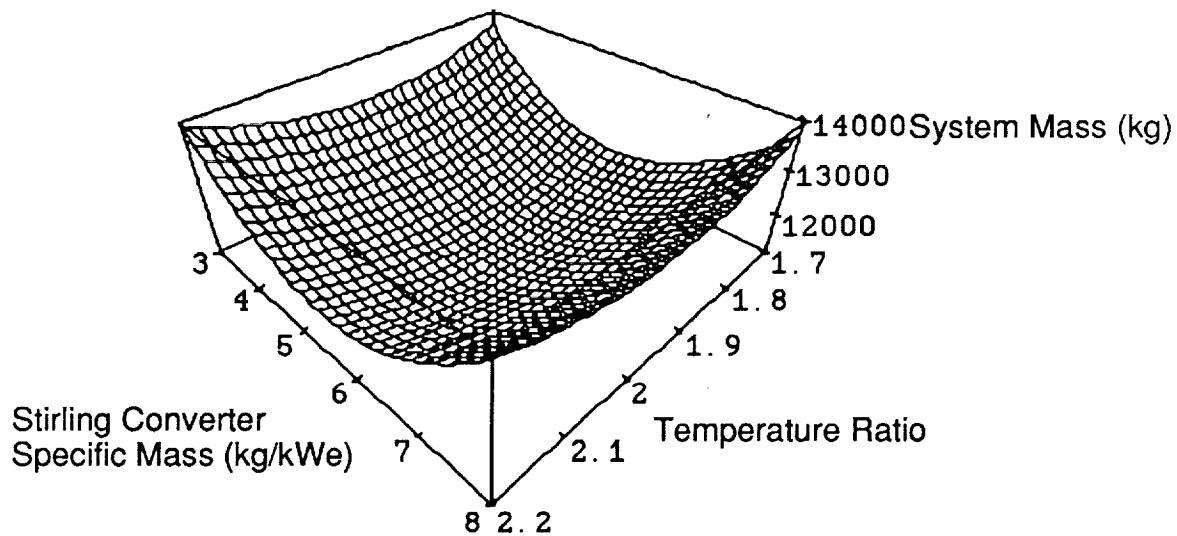


FIGURE 2. System Optimization Surface

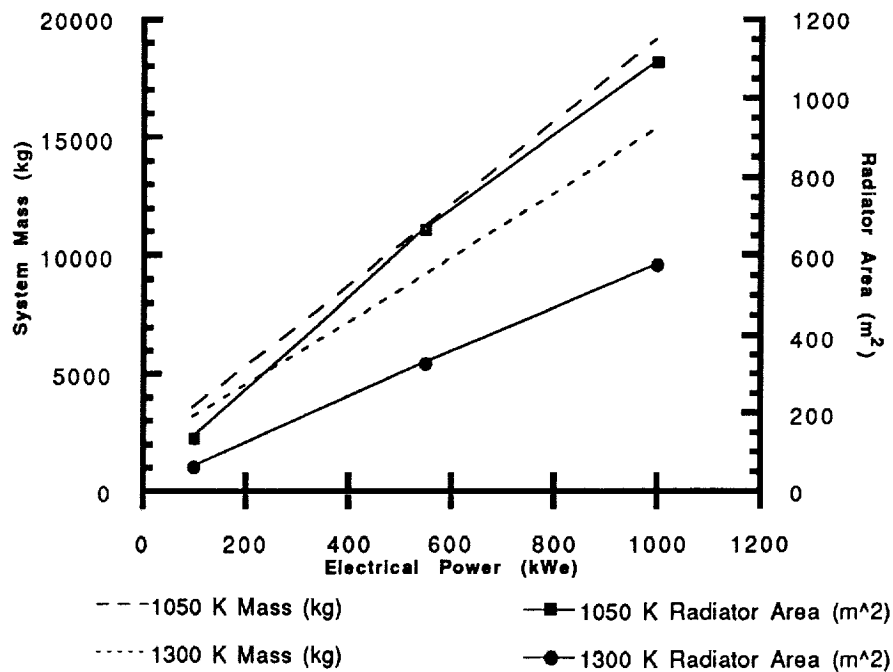


FIGURE 3. Mass and Radiator Area as a Function of Electrical Power Level

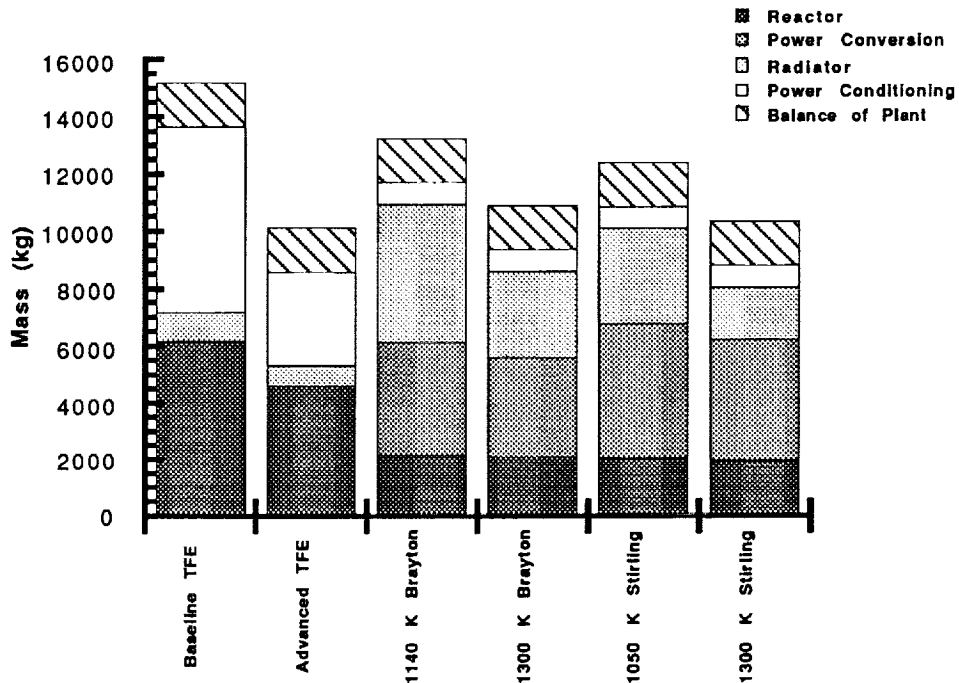


FIGURE 4. Mass Comparison of 550 kWe Systems

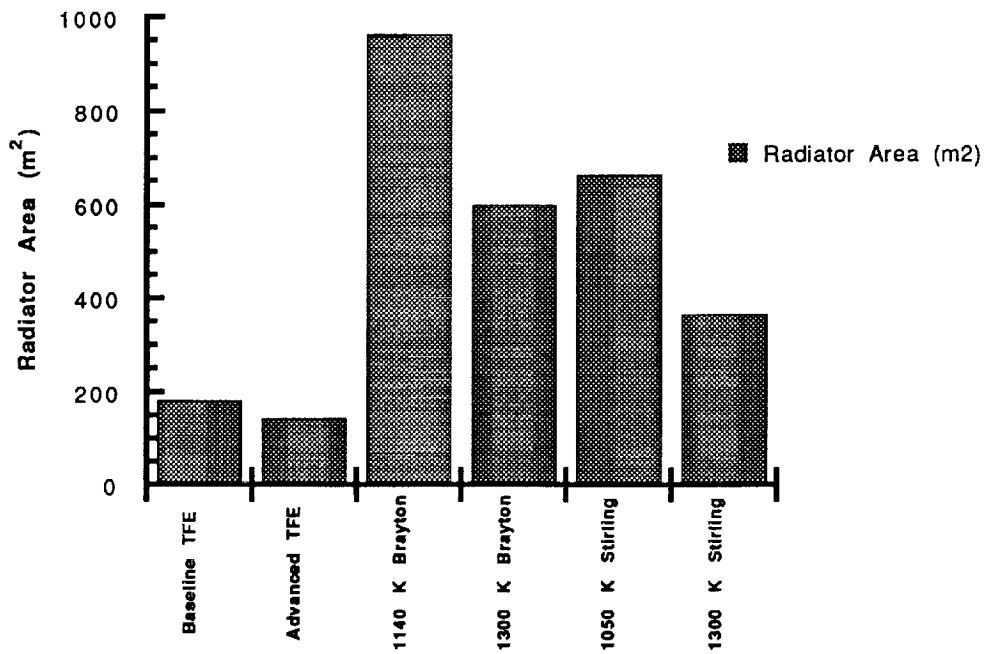


FIGURE 5. Radiator Area Comparisons of 550 kWe Systems



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16. Abstract <p>An analysis is performed to mathematically model a 550 kWe lunar base power supply which uses a SP-100 reactor coupled with Stirling converters. The reactor is placed in a excavation to keep activated coolant in the hole and to allow maintenance of the components outside the hole. Two technology levels are considered. They are 1050 K and 1300 K heater head Stirling converts. It is found that for a 1050 K converter the total mass which provides 1000 volts DC at 250 meters is 14,366 kg while the 1300 K systems mass is 12,104 kg. The radiator area of the 1050 and 1300 K systems are 641 m² and 356 m² respectively. Comparisons are made with Brayton and thermionic systems with both near term and advanced technology considered.</p>			
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